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Contract DAAG29-85-K-0080

OPTIMUM RADIATION OF SHORT-TIME DURATION SIGNALS

1 April 1985 — 30 September 1988

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Abstract

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1.0 Summary of Problems Investigated and Major Results

The major findings of this contract effort have been documented in journal publications and conference presentations and will be summarized here. Two additional studies have been conducted but the findings were judged not to be of sufficient value to warrant publication. These also are summarized below.

1.1 *Energy Maximization of Radiation from Dipole Arrays*

This task is concerned with determining the time waveform that each of the ideal, zero-impedance voltage sources should apply to the dipole array in Figure 1 in order to maximize the energy in the pulse radiated to a particular far-field point. The signal bandwidth is explicitly limited to a specified range, expressed as per cent bandwidth with respect to the center frequency. The maximization yields the most energy within a specified, short time interval when the total energy radiated by the array is normalized to 1 Joule. A typical result from $J1$ (see section 2) is shown in Figure 2, where the radiated far field waveform in the optimized direction is plotted versus $f_o\tau$; f_o is the center frequency and τ is retarded time. The waveform was optimized to have maximum energy in the interval $|f_o\tau| \leq 3$ and nearly all of the energy is confined to this interval.

1.2 *K-Pulse Techniques for Short-Pulse Radiation*

The results described in section 1.1 show how to feed an antenna in order to produce a radiated pulse with the maximum possible energy within a specified time interval when the signal bandwidth is constrained to a particular value. The K-pulse technique of Kennaugh [1] and the E-pulse technique of Rothwell, et al [2], also provide waveforms that are confined to a short time duration, although these methods assume infinite bandwidth is available. In paper $J2$, we have compared the results obtained for radiated pulses derived from the optimization method and the E-pulse method. The E-pulse method requires that the complex singularities of the antenna's transfer function be determined, and from these the required excitation voltage can be constructed. A four-element dipole array like the one in Figure 3a has been analyzed, with the feed network assumed to be an ideal power divider and time delay lines set to steer the beam to the desired direction. When the singie voltage waveform in figure 3b, which was derived by using the E-pulse technique, is passed through a 180% band-pass filter and applied to the input of the feed network, the

resulting far field energy is nearly all confined to the minimum possible duration (Fig. 3c). Comparing this wide–band result to that obtained by using the optimization procedure of *J*1, we find that the E-pulse (or K-pulse) technique yields a result equally as good as the optimum solution (99.81% energy confinement compared to 99.88% for the optimum). However, when the K-pulse waveform bandwidth is restricted to 50%, the resulting energy confinement is not nearly as good as for the optimum, which adjusts the waveform to optimally use the available bandwidth.

1.3 *Bounds on Antenna Response*

Sensitive receiver systems that are attached to antennas are subject to damage by high-voltage or high-energy pulses that may be collected by the antenna from a variety of natural and man-made sources. By using the optimizations studied under this contract, a upper bound can be established for the signal voltage or signal energy that can be delivered to a receiver from an incident waveform. The waveform is characterized by only two parameters; its bandwidth and its total energy density. Figure 4 is taken from paper *J*3 and shows the maximum voltage that can be delivered to the load attached to an 8-element dipole array when it is illuminated by a plane wave having 1 Joule/m^2 energy density within a 50% bandwidth centered at the operating frequency of the antenna. The solid curve is computed for the array steered in the direction, ϕ, of the incoming wave, while the dashed curve is computed for the array scan angle fixed to endfire ($\phi = 90^o$) while the incidence angle varies. These curves provide an upper bound on the signal level that must be accommodated by a limiter circuit. Paper *J*3 also contains waveform plots of the maximized signals.

1.4 *Target Discrimination*

The singularity expansion method [3] provides a formal expression of the late-time response of scatterers in terms of damped sinusoids that are associated with poles of the transfer function in the complex frequency domain. A waveform that is orthogonal to all of the damped sinusoids of a particular target will create a radar return that is zero in the late time. Of course this implies that the waveform must have infinite bandwidth. Nonetheless, analytical and experimental evidence by many researchers indicates that large, finite bandwidths yield discriminating waveforms that produce radar returns with most of their

energy confined to a short time duration. One of the most important features of these waveforms is that they are independent of target aspect angle.

During this contract, we have developed an algorithm based upon our optimization techniques that can generate, from measured or calculated radar returns of a known target, a discriminant waveform. This waveform is aspect independent and seems to possess the target identifying characteristics of K-pulse and E-pulse waveforms, but it can be obtained without performing the arduous task of determining the complex poles of the tangent's transfer function. The major differences we have found are associated with the bandwidth of the signal. For wide bandwidth signals, the properties of a properly derived optimization waveform are the same as those of a K-pulse or E-pulse. For limited bandwidth signals, the aspect-independent discrimination properties can be maintained, but the duration of the early-time period must be lengthened and chosen by an iterative procedure.

A typical example of target discrimination is depicted in Figure 5, where the radar return signals from various length wires are plotted. The discriminant waveform was constructed for the 1.6-m-long wire. Adequate discrimination, denoted by increased energy in the late–time period $f_o\tau > 2$, is obtained for incorrect "targets" that are 4 to 6% different in length. Several other examples are included in paper $J4$. A second paper ($J5$) describes the results of applying the optimization method to measured transient data obtained at the Michigan State University research facility and supplied to us by Dr. Ed Rothwell. That paper also will present a comparison of the results obtained by our method and Dr. Rothwell's E-pulse method.

1.5 *Load Synthesis for Control of Antenna Radiation*

Two problems have been investigated under this topic. The first, described in paper $J6$, involves the use of reactive loads and sections of transmission line in order to synthesize the excitation required to obtain a specified radiation pattern from a dipole array fed from a single generator. Series and corporate feed networks have been considered, and an algorithm has been developed for use at a single frequency. Figure 6, taken from $J6$, shows the patterns that result from an 11-element array fed by a parallel network. The transmission line impedances, Z_n, and reactive load admittances, B_n, were determined by the algorithm so that the excitation required for a 30-dB Chebyshev pattern could be

obtained, including mutual coupling effects. As can be seen in Figure 6, the operating bandwidth of the array is usually much less than that required for transient applications, but the method can be applied to narrow-band problems.

The second problem that has been investigated is the use of multiple loads along a linear antenna in order to optimize its transient radiation (Fig. 7). A field-current relationship is derived in a manner similar to Fanson and Chen [4] and then our optimization methods are employed to obtain the optimum current distribution. From that distribution, the load impedances are calculated from

$$Z_{Lm} = \begin{cases} -\dfrac{1}{I_m}\displaystyle\sum_{n=1}^{M} Z_{mn} I_n, & m \text{ not feed point} \\ \dfrac{V}{I_m} - \dfrac{1}{I_m}\displaystyle\sum_{n=1}^{M} Z_{mn} I_n, & m \text{ is feed point,} \end{cases}$$

where Z_{mn} are the moment method impedance matrix elements for the antenna, I_m are the current coefficients, and V is the generator voltage. All of these quantities are expressed as *functions of frequency* over the band of interest.

This load synthesis procedure results in much higher radiated field strengths than are achievable with a simple wire antenna, but it creates negative resistances and so is not of much practical value. Nonetheless, the optimization criterion yields an upper bound on radiation from an impedance loaded wire antenna and this bound can be used to characterize the degree of improvement that one can achieve, or has achieved, with some proposed scheme.

1.6 *Experimental Studies*

The waveforms of interest in our transient studies have extremely wide bandwidths and are not likely to be generated in real time. However, it is possible to use swept or stepped frequency data in digital processing to synthesize the desired waveform within computer memory. Therefore, one method of experimentally verifying our results involves the measurement of the transfer function of an antenna, such as a dipole array, and then using this as the starting point for the optimization algorithm. Alternatively, a computer program can "apply" the desired waveform to a digitized version of the measured transfer

function to determine if the resulting response agrees with the predictions of our theories. Yet another approach is to compute the transfer function using our algorithms and compare it directly to the measured transfer function. We have performed the two latter comparisons and obtained good results. Figure 8 shows the far-field waveform resulting from a two-element, broadside dipole array excited by a 100% bandwidth signal designed to maximize the energy in the interval $|f_o\tau| \leq 2.57$. The solid curve is obtained by using the transfer function obtained from the moment method analysis, which is the function used to generate the excitation. The dotted curve is obtained by applying this excitation to a measured transfer function for which a two element monopole array was constructed and tested in a specially designed ground-plane anechoic chamber. The empirically based result is not quite as well confined as the analytically based result, but the agreement is sufficient to provide confidence in our methods of modeling the physical structure.

2.0 Publications

The following publications resulted from work sponsored in whole or in part by this contract.

Journal Articles

*J*1. "Optimization of Pulse Radiation from Dipole Arrays for Maximizing Energy in a Specified Time Interval," Yoon-Won Kang and David M. Pozar, *IEEE Trans. Ant. and Prop.*, AP–34, 1383—1390, December 1986.

*J*2. "K-Pulse Techniques for Short-Pulse Radiation from Dipole Arrays," J.–P. R. Bayard and D.H. Schaubert, AP–36, 363—368, March 1988.

*J*3. "Transient Response of a Receiving Dipole Array: Bounds and Maximization," J.–P.R. Bayard and D.H. Schaubert, *IEEE Trans. Electromag. Compat.*, EMC–30, 122—129, May 1988.

*J*4. "Target Identification Using Optimization Techniques," J.–P.R. Bayard and D.H. Schaubert, submitted to *IEEE Trans. Ant. and Prop.*, presently being revised.

*J*5. "Comparison of Optimization Method and E–Pulse Method for Target Discrimination," J.–P.R. Bayard, D.H. Schaubert and E.J. Rothwell, in preparation.

J6. "Pattern Synthesis Using Reactive Loads and Transmission Line Sections for a Singly Fed Array," Y.W. Kang and D.M. Pozar, accepted for *IEEE Trans. Ant. and Prop.*

Conference Papers

C1. "K-Pulse Techniques for Short-Pulse Radiation for Dipole Arrays," *1987 IEEE Int'l. Sym. on Ant. and Prop.*, 958—961, Blacksburg, VA.

C2. "Pulse Energy Maximization Applied to Target Discrimination," J.-P. R. Bayard and D.H. Schaubert, *1988 IEEE Int'l. Sym. on Ant. and Prop.*, 656—659, Syracuse, NY.

3.0 Students Supported and Degrees Earned

The followng students were supported or partially supported by this contract. Degrees earned during the contract period are noted by the date of completion.

J. Bayard, M.S. 1986

Y. Kang, Ph.D. 1986

B. Kaufman, M.S. 1988

J. Bayard, Ph.D. candidate

E. Dziadek, M.S. candidate

D. Lathrop, M.S. candidate

4.0 References

1. E.M. Kennaugh, "The K-pulse concept," *IEEE Trans. Antennas and Propagat.*, vol. AP-29, No. 2, pp. 327—331, Mar. 1981.

2. E. Rothwell, D.P. Nyquist, K. Chen and B. Drachman, "Radar target discrimination using the extinction-pulse technique," *IEEE Trans. Antennas Propagat.*, vol. AP-33, no. 9, pp. 929-936, Sept. 1985.

3. C.E. Baum, "On the Singularity Expansion Method for the Solution of EM Interaction Problems," *AFWL Interaction Note 88*, 1971.

4. P.L. Fanson and K.-M. Chen, "Modification of Antenna Radiating Characteristics with Multi-Impedance Loading," *IEEE Trans. Antennas Propagat.*, vol. AP-21, no. 5, pp. 715—721, Sept. 1973.

5. J.-P.R. Bayard, "Kill-Pulse Techniques for Short Pulse Radiation from Dipole Arrays," Masters Thesis, University of Massachusetts, September 1986.

Figures

1. Geometry of an N-element equispaced linear array of dipoles with N independent, ideal voltage sources.

2. Time far-zone optimized electric field for eight-element dipole array operating endfire. Element spacing = 0.3 wavelengths at center frequency, bandwidth = 50%, energy maximized in $|f_o\tau \leq 3$.

3. Typical result obtained by using K-pulse technique for wide-bandwidth signal. (a) Linear dipole array with corporate field and single generator. (b) Time-domain K-pulse voltage for four-element dipole array (element length = 0.5 m, diameter = 0.001 m, spacing = 0.5 m). (c) Far-zone radiated field of four-element dipole array at $\theta = 45^o$, $\phi = 0^o$ for 180% bandwidth.

4. Maximum amplitude of load voltage versus incidence angle in the H-plane for 8-element dipole array. Element length and spacing is $\lambda_o/2$ at center of band.

5. Voltages received when discriminant waveform for 1.6-m-long target is applied to targets of various length. Radar antenna is 0.5-m-long dipole and bandwidth is 150%, centered at $f_o = 93.75$ MHz resonance of target.

6. Results of using load synthesis for 11-element array fed by parallel feed network. (a) Radiation pattern at three frequencies for 30-dB Chebyshev design. (b) Schematic of antenna.

7. Geometry of wire antenna with M lumped loads.

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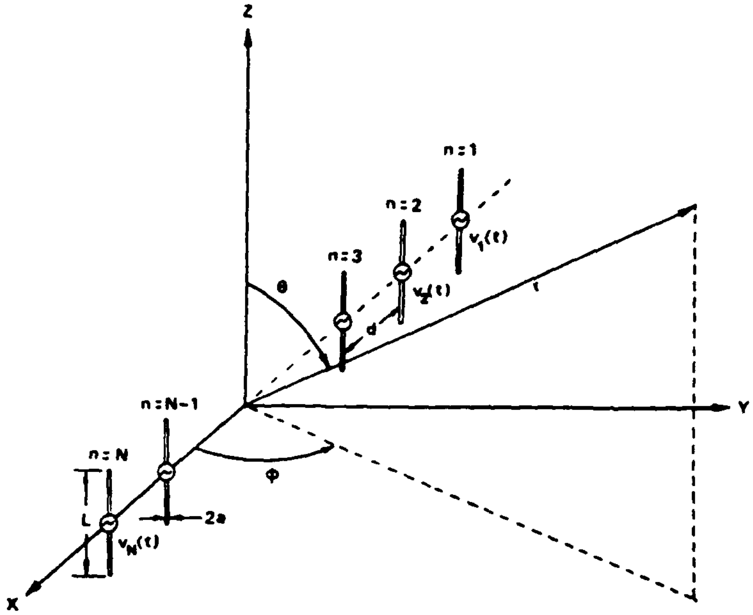

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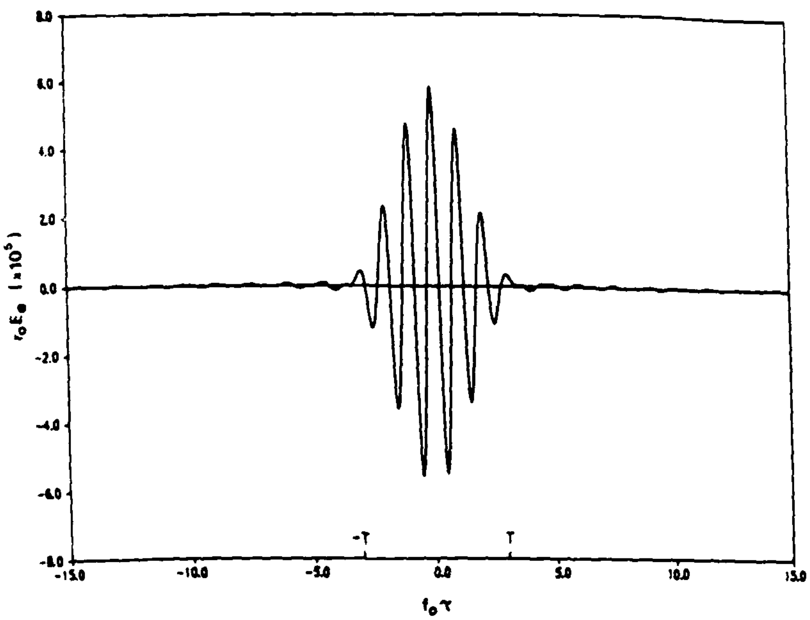

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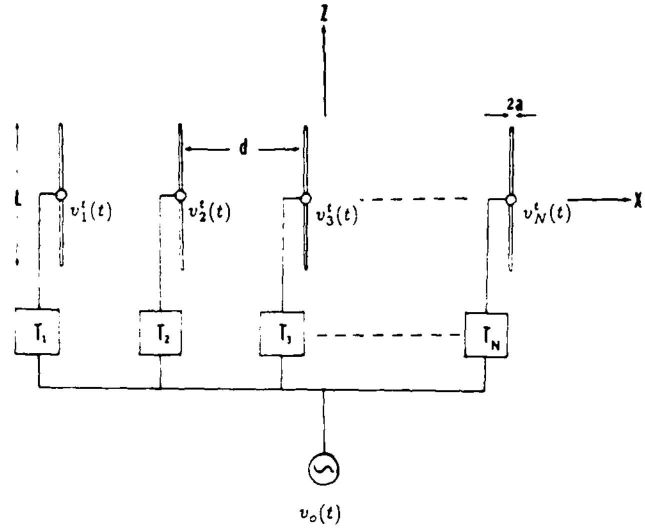

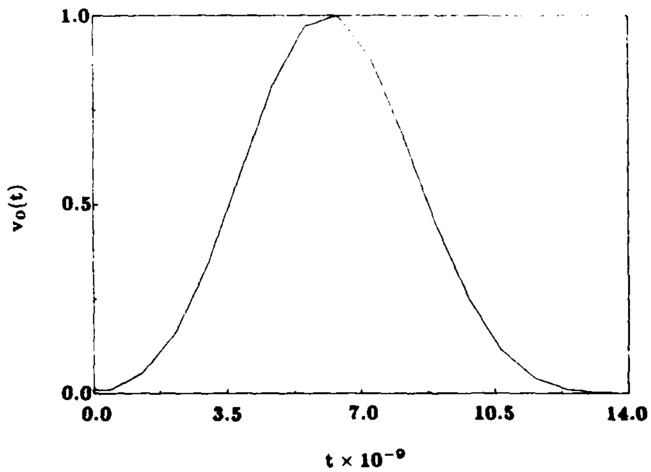

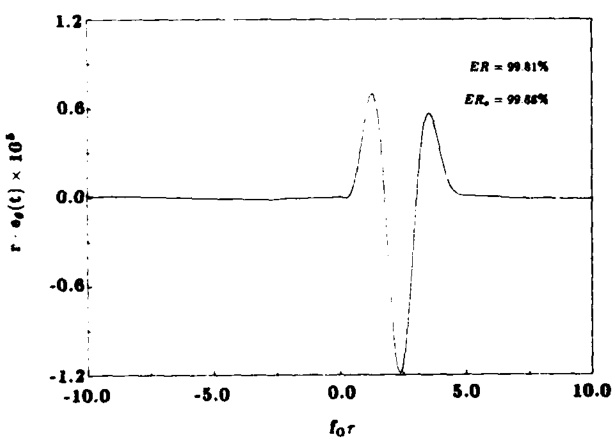

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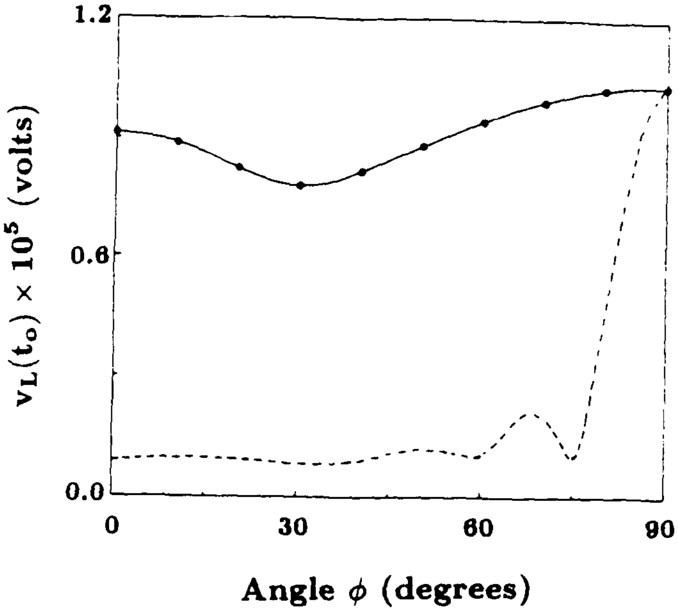

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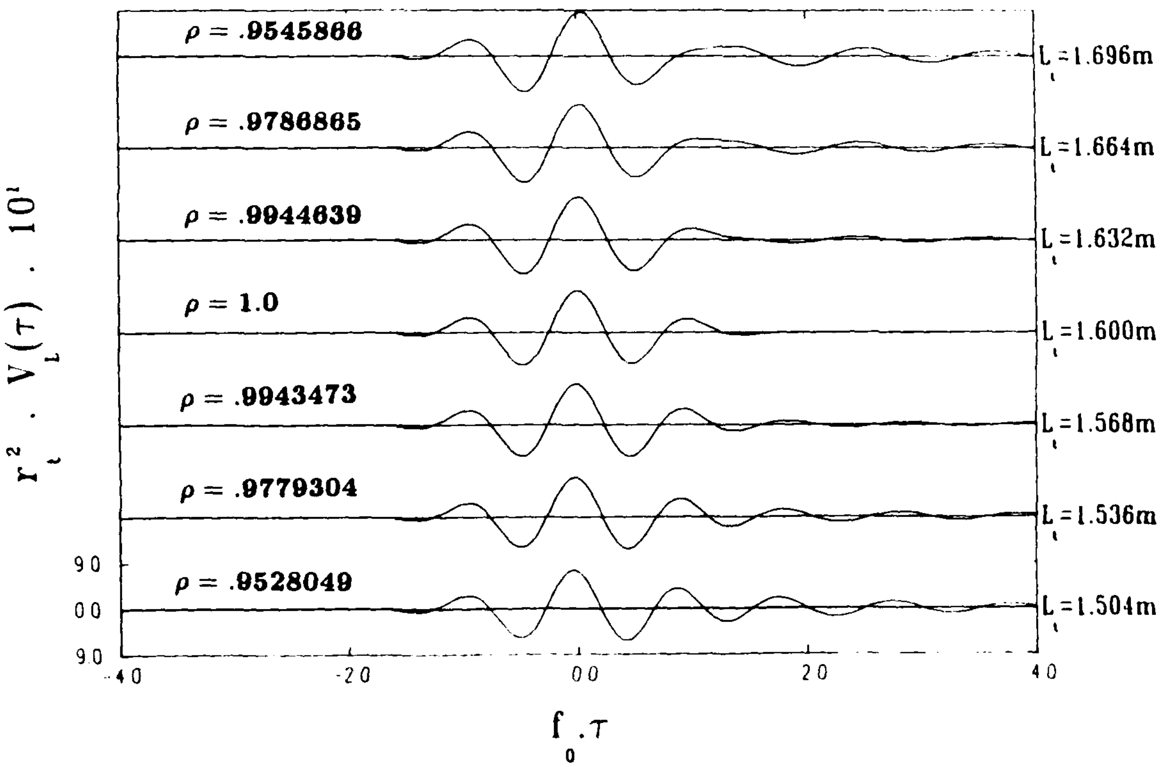

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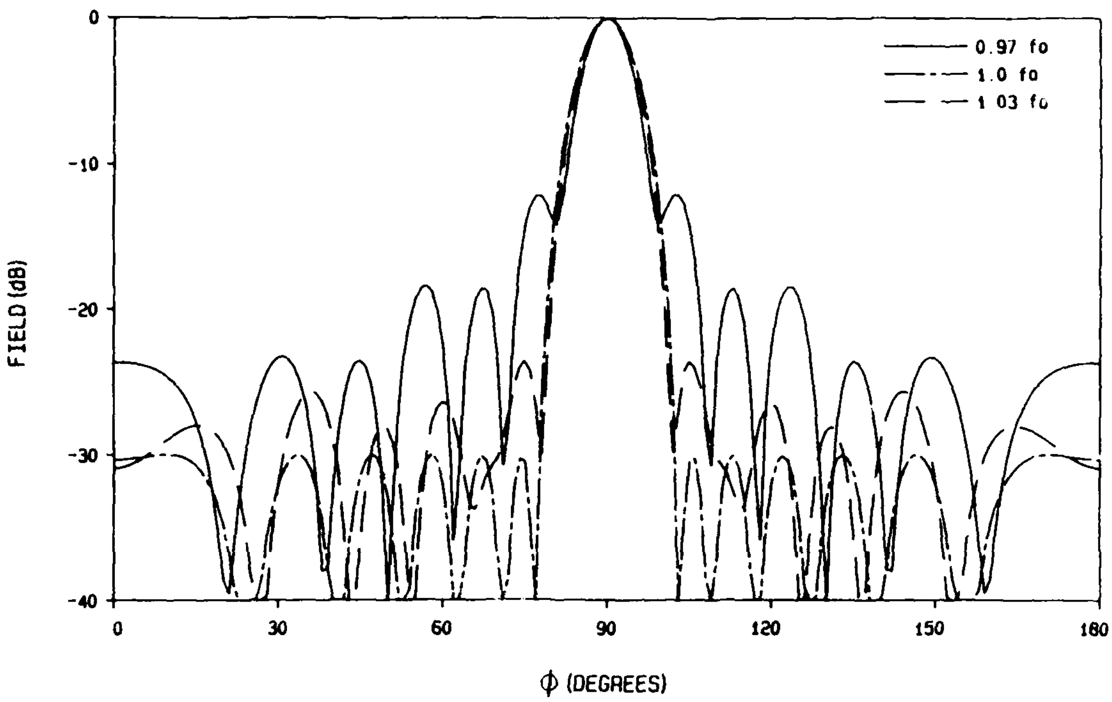

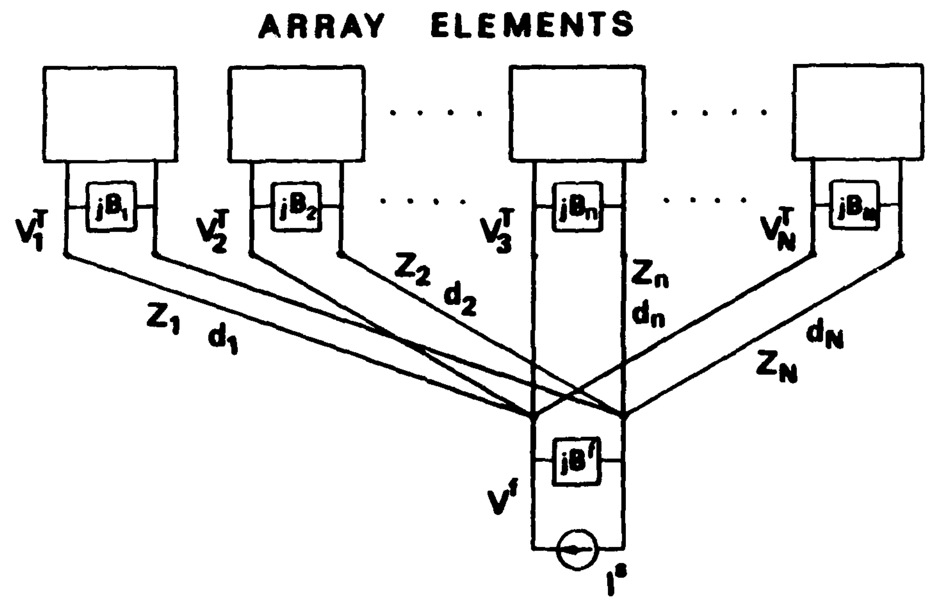

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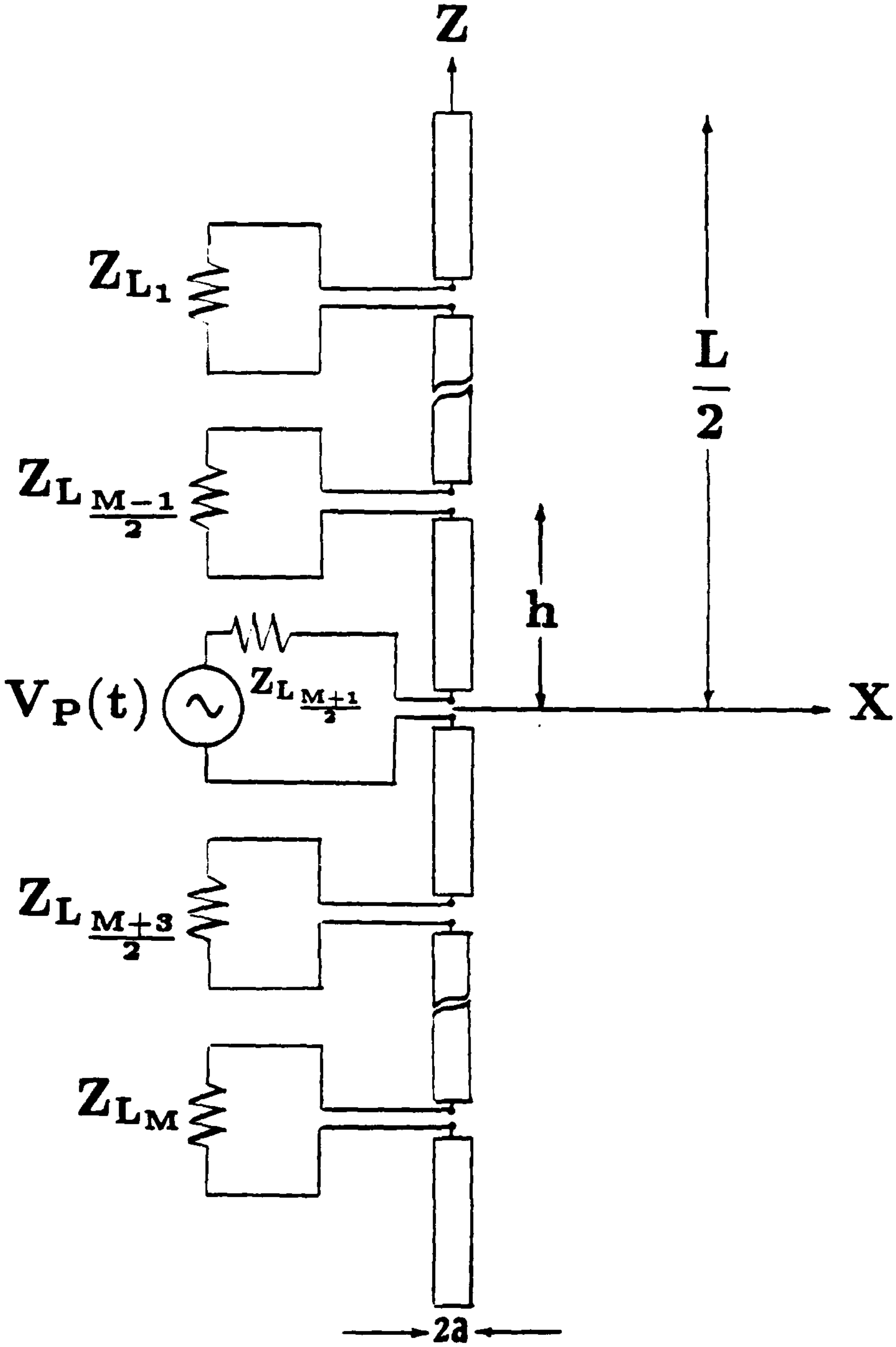

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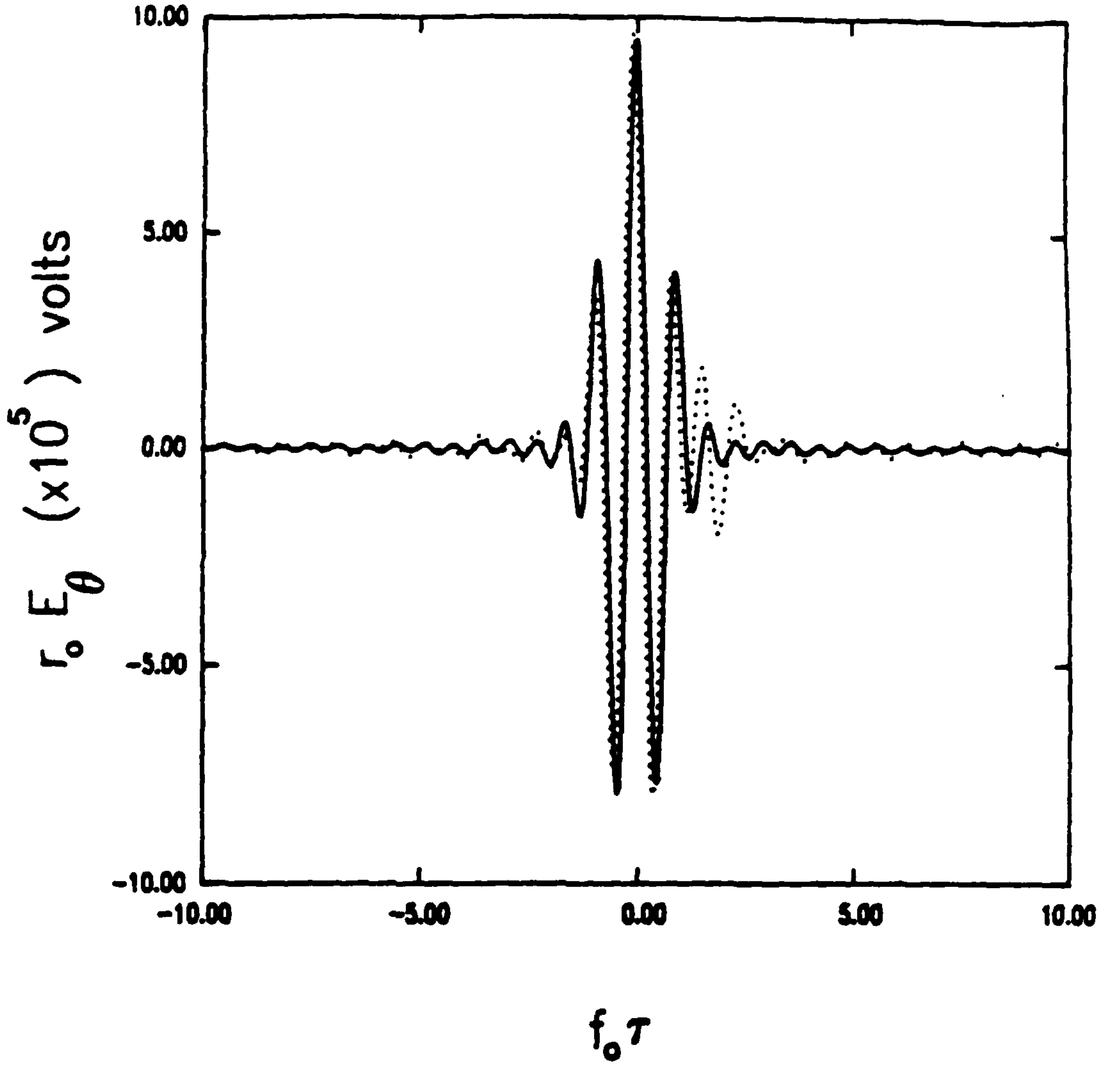

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